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Old stellar disks and the origin of S0 galaxies

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Abstract. We studied stellar population properties and their variations along the radius in 21 nearby S0 galaxies. By calculating Lick indices H-beta, Mgb, Fe5270, and Fe5335, we have estimated SSP-equivalent ages, metallicities, and magnesium-to-iron ratios in their large-scale stellar disks. We have found mostly magnesium overabundant stellar populations in the disks, [Mg/Fe]> +0.2, and in 14 of 21 the mean stellar ages are larger than 11 Gyr. The large ages and magnesium-to-iron overabundance of the outer disks of nearby S0s contradict the commonly accepted scenario of S0 galaxy formation from spirals by quenching their star formation during infall into dense environments at intermediate redshifts, $z = 0.4 - 0.5$ (4–5 Gyr ago). We propose a new scenario according to which S0 galaxies as a class are a primordial type of disk galaxies forming at $z > 2$ from highly-turbulent gaseous clumpy disks. Many of them become later spirals by accreting external high-momentum cold gas, smoothly inflowing on the prolonged timescales and giving a rise to thin disks. In dense environments cold gas accretion is difficult to retain, so the majority of primordial S0s in clusters and rich groups have remained S0s becoming the dominant galaxy population there at $z = 0$.

Key words. galaxies: elliptical and lenticular, cD — galaxies: evolution

1. Introduction

Lenticular and spiral galaxies are very similar as concerning their global structure: both morphological types imply composite structure consisting of two large-scale stellar components, a spheroidal bulge and an extended flat disk. However, they look quite different, mostly due to a lot of blue details over the disks of spiral galaxies caused by intense current star formation; the very spiral arms are an extreme example of such details. The existence of spiral arms being thought to result from wave disturbances of the disk surface density implies also the dynamical 'coolness' of the disks which may be related as well to young stars and cold gas presence. If one succeeds to remove gas and stop star formation in a disk of a spiral galaxy, it would transform immediately into a lenticular one. Another difference among lenticulars and spirals is their location preference: spirals dominate in the field – up to 72% of all the galaxies (Naim et al. 1995), lenticulars dominate in clusters – up to 60% of all galaxies (Dressler 1980). In intermediate-mass conglomerates, namely in groups, spirals and lenticulars constitute equal parts, 40% – 45% each (Postman & Geller 1984). Up to this point, only observational facts play; but further cosmological models give crucial impact into our way of thinking. Indeed, if the

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Universe large-scale structure develops hierarchically, and clusters form later than groups, it seems natural to suppose that spirals galaxies (of the field) have transformed into lenticulars (of groups and clusters) when falling into dense environments during hierarchical dark mass assembly. Yes, a spiral galaxy can be transformed into a lenticular one by removing gas and ceasing star formation; but a lenticular galaxy can be transformed into a spiral one by adding gas and starting star formation quite as natural. The assumed direction of disk galaxy evolution has been selected through the model approach. However, the LCDM cosmology is now a high-precision quantitative model, and it defines strict timescales for all the processes of mass assembly. We know that clusters have assembled mostly **after** $z = 1$, and there are also observational evidences that at $z = 0.4$ their galaxy population changes drastically: blue (spiral?) galaxies are replaced by red (lenticular?) ones (Dressler et al. 1997; Fasano et al. 2000). Moreover, the galaxy population of groups changes quite synchroneously, from Ss to S0s, just at the same redshift (Wilman et al. 2009; Just et al. 2010). Do we see there the S0 galaxy arising as a class? Many peoples think so. But it means that only 5 Gyr ago our nearby S0s of the clusters and groups were spirals and proceeded star formation in their disks on rather long timescales. We should then expect that the mean (SSP-equivalent) age of the stellar populations in the large-scale disks of the nearby S0s is to be less than 8 Gyr (Smith et al. 2009; Allanson et al. 2009), and magnesium-to-iron ratio of the stars is to be solar, similarly to thin disks of nearby spirals. This conclusion was just what we could probe, and we undertook a study of the stellar population properties in the large-scale disks of nearby S0 galaxies.

2. Observations

We have analysed deep long-slit spectral data for 21 nearby S0 galaxies obtained with the reducer SCORPIO of the Russian 6m telescope (Afanasiev & Moiseev 2005). The sample, though being rather small, covered a range of luminosities and environment types. We took exposure times long enough, to reach outer disks of our targets with a signal-to-noise ratio sufficient to analyse stellar population properties by using Lick indices (Worthey 1994; Worthey et al. 1994). The Lick indices Hβ, Mgb, Fe5270, and Fe5335 were traced up to the radii of 2–4 exponential scalelengths for the disks under consideration; the Lick index system was checked permanently by observing the Lick standard stars (Worthey et al. 1994) every observational run. Then the indices measured in the galaxies were compared with the simple stellar population (SSP) models by Thomas, Maraston, & Bender (2003) to derive stellar population properties: mean ('SSP-equivalent') age, metallicities, and magnesium-to-iron ratio. The latter characterisctics is especially important to evaluate typical duration of star formation in the S0 disks; the models by Thomas, Maraston, & Bender (2003) are calculated for 3 various [Mg/Fe] values and so allow to estimated the mean stellar magnesium-to-iron ratios of the disks (and bulges) of the galaxies under consideration.

3. Results

We have published the results on 15 galaxies from this sample in our paper by Sil'chenko et al. (2012) Our results on the stellar population property diagnostics in the disks of all 21 S0s are shown in Fig. 1.

One can see that the disks are mostly old, with 14 of 21 (67%) ones being older than 11 Gyr, and also magnesium overabundant, with the majority disks having [Mg/Fe]= +0.2 – +0.3. All the disks which are surely younger than 11 Gyr but one are located in sparse environments. The metallicity reaches solar value only in the youngest disks; in other disks it concentrates around [Z/H]= −0.4 – −0.2.

4. Discussion

Our results if been confirmed on a larger sample put an end to the hypothesis that a bulk of S0 galaxies were formed at $z = 0.4 - 0.5$ in dense environments by quenching star formation in disks of spiral galaxies. Indeed, the SSP-equivalent age of 11 Gyr means that the

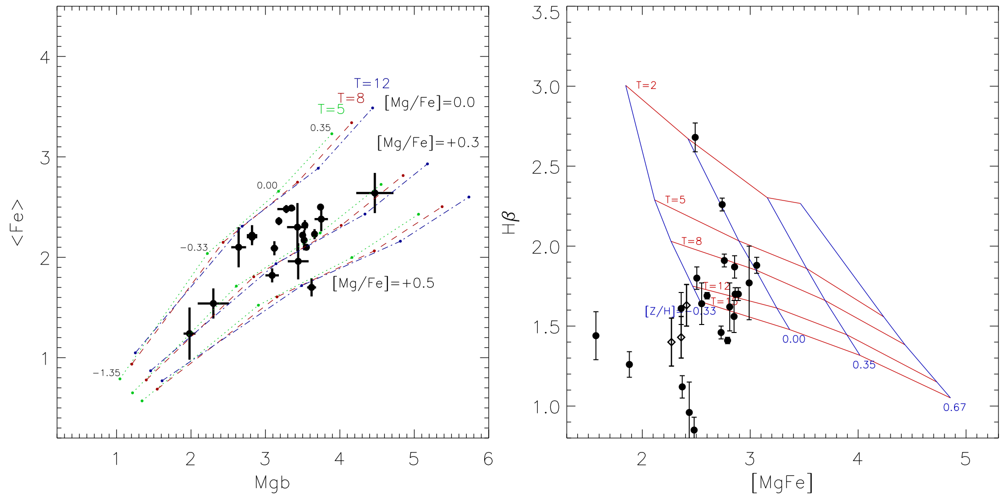

Fig. 1. Diagnostic index-index diagrams for the outer disks averaged over their full extension. **(a)** – The ⟨Fe⟩ vs Mgb diagram. The black dots are our galaxies' disks with their measured index errors. The simple stellar population models by Thomas, Maraston, & Bender (2003) for three different magnesium-to-iron ratios (0.0, +0.3, and +0.5) and three different ages (5, 8, and 12 Gyr) are plotted as reference. The small signs along the model curves mark the metallicities of +0.35, 0.00, –0.33, and –1.35, if one takes the signs from right to left. **(b)** – The age-diagnostic diagram for the stellar populations in the outer disks of the galaxies under consideration. The stellar population models by Thomas, Maraston, & Bender (2003) for [Mg/Fe]= +0.3 and five different ages (2, 5, 8, 12 and 15 Gyr, from top to bottom curves) are plotted as reference frame; the blue lines crossing the model metallicity sequences mark the metallicities of +0.67, +0.35, 0.00, –0.33 from right to left. Three globular clusters of our Galaxy, with intermediate metallicities of [Fe/H]= −0.4 – −0.7, are also plotted by diamonds for comparison; their indices are taken from Beasley et al. (2004).

star formation ceased 10 Gyr ago ad minimum (Smith et al. 2009; Allanson et al. 2009) which corresponds to the redshift $z \approx 2$; and the magnesium overabundance signifies a very brief duration of this star formation, less that 1 Gyr. We can indicate a close analog of the S0 disks studied here – it is a thick disk of our own Galaxy. Its parameters – the age larger than 10 Gyr, [Mg/Fe]> +0.2, [Z/H] (close to [O/H]) between 0.0 and −0.7 (Bernkopf & Fuhrmann 2006; Schuster et al. 2006) – resemble those obtained for S0s. Detailed data give evidence for a time lag between the complete formation of the thick disk and a start of formation of the thin disk in our Galaxy, so during 1–2 Gyr, just between $z = 2$ and $z = 1$, our own Galaxy **was** a lenticular one! Moreover, we can also indicate high-redshift galaxies which can be true progenitors of the modern S0s – these are massive clumpy star-forming disks at $z > 1.5$. The statistics of visible galactic morphology at $z > 1-1.5$ reveals a progressive lack of well-known Hubble galaxy shapes; instead a dominance of clumpy irregular types emerges: of chains, nests, 'head-tails', etc. (van den Bergh et al. 1996; Elmegreen et al. 2005). Kinematical analysis proves that the 'chains' and 'nests' are in fact gravitationally bound and represent SF sites within disks with the typical sizes of 1–1.5 kpc that restricts the typical heightscales of the disks containing clumps. SPH simulations of secular evolution for such a clumpy disk promise very effective (and so brief) star formation after end of which the thick disks with magnesium-overabundant stellar population must arise (Bournaud et al. 2007, 2009). Basing on the arguments listed above, I propose a new scenario of disk galaxy evolution during the last 10 Gyr. All disk galaxies were initially, 10 Gyr ago, S0s, with their thick stellar disks built in short intense star formation bursts at $z \geq 2$. Later, at $z < 1$, or < 8 Gyr ago, most of them met some sources of cold gas accretion from outside; those became spirals. Within dense environments, in clusters and massive groups with their hot intracluster/group medium, it is difficult for the outer gas to remain cold – so the most primary S0s in clusters and groups have to remain S0s up to now. Perhaps also the harrassment in dense environments strips away cold gas reservoirs preventing further thin disk formation. A class of S0s in sparse environments which demonstrates sometimes the outer stellar disks of intermediate age may be related to random orientation of outer cold gas accretion: if the accretion flow is strongly inclined to the galactic plane, perhaps the resulting gaseous disk would not be cool enough to start steady long-lasting star formation.

With this new scenario we can explain some observational facts which remain puzzles up to now, including: S0s are in average fainter than the neighboring types, Es and Sas (van den Bergh 2009); S0s have fainter disks than Sa-Sb at a fixed bulge luminosity (Laurikainen et al. 2010), and the bulges of S0s are in average fainter than those of early spirals (Graham & Worley 2008); the Tully-Fisher relation of S0s in the K-band is shifted down with respect to that of spirals (Williams, Bureau, & Cappellari 2010). All these statistical features leave a good room for S0s to build up their thin disks while finding sources of gas accretion at intermediate redhifts – at intermediate stages of their evolution – to become spirals.

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References

Afanasiev V. L., & Moiseev A. V. 2005, Astronomy Letters, 31, 194
Allanson S. P., Hudson M. J., Smith R. J., Lucey J. R. 2009, ApJ, 702, 1275
Beasley M., et al. 2004, AJ, 128, 1623
Bernkopf J., Fuhrmann K. 2006, MNRAS, 369, 673
Bournaud F., Elmegreen B. G., Elmegreen D. M. 2007, ApJ, 670, 237
Bournaud F., Elmegreen B. G., Martig M. 2009, ApJ, 707, L1
Dressler, A. 1980, ApJ, 236, 351
Dressler A., et al. 1997, ApJ, 490, 577
Elmegreen D. M., Elmegreen B. G., Rubin D. S., Schaffer M. A. 2005, ApJ, 631, 85
Fasano G., Poggianti B. M., Couch W. J., Bettoni D., Kjaergaard P., Moles M. 2000, ApJ, 542, 673
Graham A. W., Worley C. C. 2008, MNRAS, 388, 1708
Just D.W., Zaritsky D., Sand D. J., Desai V., Rudnick G. 2010, ApJ, 711, 192
Laurikainen E., Salo H., Buta R., Knapen J. H., Comeron S. 2010, MNRAS, 405, 1089
Naim A., et al. 1995, MNRAS, 274, 1107
Postman M. & Geller M. J. 1984, ApJ, 281, 95
Schuster W. J., Moitinho A., Marquez A., Parrao L., Covarrubias E. 2006, A& A, 445, 939
Sil'chenko O. K., Proshina I. S., Shulga A. P., Koposov S. E. 2012, MNRAS, 427, 790
Smith R. J., et al. 2009, MNRAS, 392, 1265
Thomas D., Maraston C., & Bender R. 2003, MNRAS, 339, 897
van den Bergh S. 2009, ApJ, 694, 120
van den Bergh S., et al., 1996, AJ, 112, 359
Williams M. J., Bureau M., Cappellari M. 2010, MNRAS, 409, 1330
Wilman D. J., Oemler A., Mulchaey J. S., McGee S. L., Balogh M. L., Bower R. G. 2009, ApJ, 692, 298
Worthey G. 1994, ApJS, 95, 107
Worthey G., Faber S.M., González J.J., Burstein D. 1994, ApJS, 94, 687